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Pure phase correlator with photorefractive filter memory

M. Duelli, A. R. Pourzand, N. Collings, and R. Dändliker

Institute of Microtechnology, University of Neuchâtel, Rue A.-L. Breguet 2, CH-2000 Neuchâtel, Switzerland

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We report on the investigation of a new compact configuration of an inverted VanderLugt-type correlator system. The phase of the Fourier transform of the image to be recognized is displayed on a phase-modulating electrically addressed spatial light modulator. This phase display is compared with the phase of the Fourier transforms of a reference library recorded in a photorefractive $LiNbO_3$ crystal. Angular hologram multiplexing permits fast data access, and the use of the conjugated replica of the stored templates leads to an elimination of phase distortions introduced by the optical system. With such a configuration, the correlator is fully shift invariant in spite of the photorefractive crystal thickness and has good discrimination with sharp correlation peaks.

Pure phase correlation[1] uses only the phase information of the object and a template; i.e., it takes the phase distribution of the Fourier transform of the object to be recognized and correlates it with the phase-only filter defined by Horner and Gianino.[2] This type of correlator shows sharp correlation peaks, a high light efficiency, and a high discrimination capability. It is mathematically equivalent to inverse filtering.[3] The phase distributions are implemented with twisted nematic liquid-crystal television (LCTV) screens that can be updated within a few tens of microseconds. However, the correlation of a single input image with a single filter at video rate limits the correlation speed. Previously high-capacity optical memories were combined with correlators where reference objects were stored on optical disks[4] or as phase holograms in photorefractive crystals[5] and sequentially loaded into the correlator, permitting a fast search through the reference library.

We built a compact hybrid digital–optical correlator system that performs pure phase correlation. A commercially available LCTV is used as a phase-only input device for the phase distribution of the Fourier transform of the input object, and a photorefractive crystal serves as a holographic memory for the storage of a library of reference objects. Thus the real-time performance of spatial light modulators (SLM's) is combined with the high storage capacity and the fast data access of volume holographic memories. It is also possible to update or refresh the holographic memory.

In classical 4-*f* correlator systems the size of the filter has to be matched to the size of the Fourier transform of the input image. If a SLM is used in the filter plane this requirement leads most often to a large focal length of the Fourier-transform lens and thus to a large overall size of the whole system. A high-quality lens and SLM must be used to minimize aberrations. An adjustment sensitivity of a few micrometers perpendicular to the optic axis and a few tens of micrometers along the optic axis has to be fulfilled to yield correct results. Moreover, for a nonquadratic pixel size of the SLM an anamorphic imaging system must be built or the filter changed electronically to correct for the aspect ratio. To avoid these requirements we use the same optical setup for the storage of the reference objects and for the correlation of the input image with the stored reference objects.

The experimental setup of our system is shown in Fig. 1. During storage of the reference objects in the photorefractive crystal, Shutter 1 is open and Shutter 2 is closed. The beam from an Ar^+ laser (wavelength $\lambda = 488$ nm) is split into an object beam, which illuminates the LCTV, and a plane-wave reference beam. The phase function $\phi(u, v)$ of the Fourier transform of the object to be stored is calculated by software as a 512×512 matrix from the original object, which is also given as a 512×512 matrix. It is displayed on the LCTV, which works in the phase-modulation regime.[6] The transmitted light is then collected by a lens and interferes with the reference beam in the photorefractive $LiNbO_3$:Fe (>0.1 mol. %) crystal, where a phase hologram is written. We use the 90° geometry; i.e., the crystal is a 45° cut with a size of 10 mm × 10 mm × 7 mm. Its low dark conductivity leads to a storage time of a few weeks in the dark. For hologram multiplexing the angular encoding scheme is utilized by rotation of the storage crystal by $\Delta\theta = 0.025°$ for each consecutive hologram. The holograms were recorded with 30 cycles in the incre-

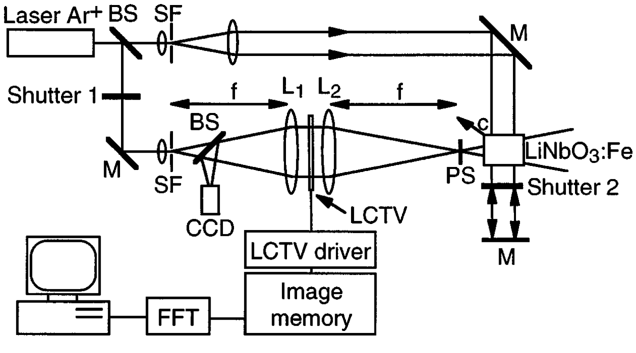

Fig. 1. Experimental setup of the phase-only correlator system: BS's, beam splitters; SF's, spatial filters consisting of a 20× microscope objective and a 10-μm pinhole; M's mirrors, L_1, L_2, lenses; *f*'s, 200 mm; PS, point stop, with diameter μm; FFT, fast Fourier transformer; c, direction of the *c* axis.

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mental recording schedule[7,8] and a writing time of 5 s per image per cycle. The writing intensities of the modulated object wave I_{ob} and the plane reference wave I_{ref} are approximately $I_{\mathrm{obj}} = I_{\mathrm{ref}} = 9\ \mathrm{mW/cm^2}$. Because a defocused edge-enhanced image is stored in the photorefractive crystal, there is no dynamic range limitation as is the case in the storage of Fourier transforms, in which the amplitudes of the object and of the reference beams are equal only over a narrow range of spatial frequencies.

The SLM consists of a liquid-crystal display taken from an Epson VPJ700 video projector. The resolution is 320×220 pixels, with a pixel size of $80\ \mu\mathrm{m} \times 90\ \mu\mathrm{m}$. The screen acts as a multilevel phase hologram that generates superimposed diffraction orders.[9] The coefficients of the diffraction orders depend on the phase matching and the coupled amplitude modulation. The first order is the ideal phase-only response but with reduced light efficiency (typically 70%); i.e., an edge-enhanced object is reconstructed by the high-pass filtering effect if only the phase information of a Fourier-transformed object is considered. The zero order yields a central spot situated at the optic axis of the system, and the minus first order corresponds to the ghost image. An object that is reconstructed from the displayed phase function in the focal plane of lens L_2 is shown in Fig. 2. The zero and first orders are clearly visible; higher diffraction orders appear as noise in the edge-enhanced object. The rectangular pixel shape leads to an aspect ratio of the reconstructed object that is different from that of the original. During recording of the reference library a point stop blocks the central spot at the focal plane of lens L_2. A rectangular aperture at the same place eliminates the higher diffraction orders that arise from the pixellation of the LCTV.

To perform pure phase correlation we set the crystal at the angle corresponding to the first stored filter. Shutter 1 is closed, and Shutter 2 is opened. The crystal is illuminated with the reference beam, and the transmitted beam is retroreflected by a simple mirror. A phase-conjugated replica of the wave that has been stored at this angle is diffracted and returns to the LCTV. The phase function $\exp[\phi_{\mathrm{input}}(u, v)]$ of the Fourier-transformed object to be recognized, which is again calculated by software, is displayed on the LCTV. The displayed phase function $\exp[\phi_{\mathrm{input}}(u, v)]$ and the retrieved and conjugated phase function $\exp[-\phi_i(u, v)]$ are multiplied in the LCTV plane. The Fourier transformation of this phase distribution, which is performed by lens L_1, results in correlation between the edge-enhanced reference object and the edge-enhanced input object. The intensity distribution $I(x, y)$ that is observed in the correlation plane, i.e., the focal plane of lens L_1, when the ith stored object is retrieved is given by

$$I(x, y) = |\mathrm{FT}\{\exp[j\phi_{\mathrm{input}}(u, v)]\exp[-j\phi_i(u, v)]\}|^2, \tag{1}$$

where FT denotes the Fourier transformation.

The autocorrelation gives a delta function; therefore we expect to detect sharp correlation peaks. The correlation plane is imaged onto a CCD camera. By rotating the crystal we sequentially retrieve the reference objects and correlate them with the input object. In order not to erase the holograms during readout, we strongly decrease the intensity of the reference plane wave compared with the recording intensity. The intensity of the incident light at the crystal is approximately $I = 140\ \mu\mathrm{W/cm^2}$. Alternatively, holograms could be thermally fixed in the crystal. Because a conjugated wave is used, phase distortions introduced by the nonflatness of the LCTV and the Fourier-transform lenses are canceled, and simple lenses can be used. Moreover, there is no need to correct for the aspect ratio, and the system is compact and easily adjusted.

The experimental results of the autocorrelation and the cross-correlation of an input object composed of the three stored objects are shown in Fig. 3. The surface plot of the interesting region of the correlation plane covers only 10% of the whole correlation plane. Because of the pure phase correlation, we obtain a good discrimination capability with sharp autocorrelation peaks. The noise in the surface plots arises from the part of the reconstructed edge-enhanced object that is not coupled into the correlation peak. Thus for a heavily covered input object the noise is the greatest. It should be noted that the noise in this system is reduced because we filtered out the zero-order component when recording the library in the crystal.

The number of input objects that can be recognized per second in this system depends on the update rate of the SLM. Currently the phase transformation of the Fourier-transformed input object is performed with software. However, a real-time electronic fast-Fourier-transform board[10] would permit an update of the LCTV at video rate. The correlation speed is determined by the time required for the presentation of a new filter. This access time of the holographic memory depends on the rotation speed of the photorefractive crystal and the angular separation of the holograms. With the crystal mounted upon a stepper-motor-driven rotation state we can read out approximately 1000 holograms/s in a continuous movement. An increase in crystal length increases the number of templates per angle and thus the

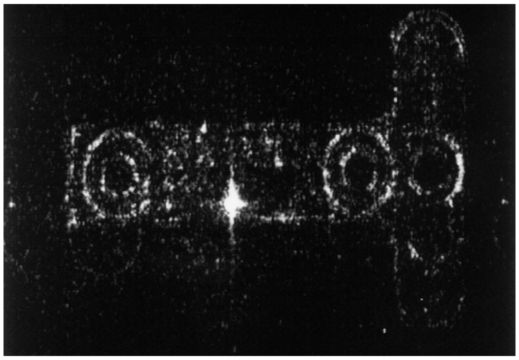

Fig. 2. Reconstructed object from the phase-only filter observed in the focal plane of lens L_2. The LCTV acts as a multilevel phase hologram, leading to superimposed diffraction orders.

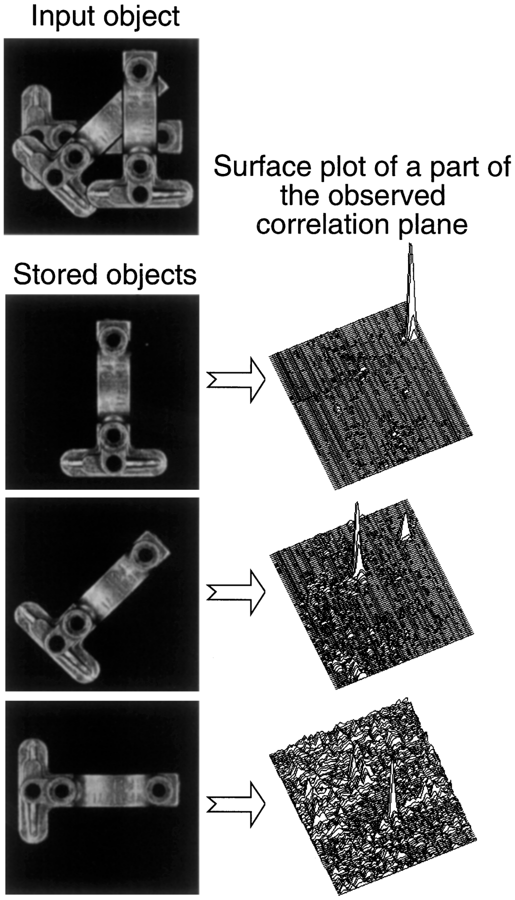

Fig. 3. Three phase filters that had been calculated from the three objects shown were stored in the photorefractive crystal. The surface plots show the intensity distribution obtained in the correlation plane when the phase filter of the input object was displayed on the LCTV and the corresponding filter was read out from the holographic memory. The surface plot covers only 10% of the whole correlation plane.

number of correlations that can be performed per second at the same angular velocity of the storage crystal. At present, the number of correlations per second is limited by electronic and electromechanical components.

In conclusion, the system combines a holographic volume memory for fast and parallel data access and a real-time updatable liquid-crystal television in an optical correlator. Shift-invariant pattern recognition with sharp correlation peaks and high discrimination can be performed owing to the pure phase correlation.

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